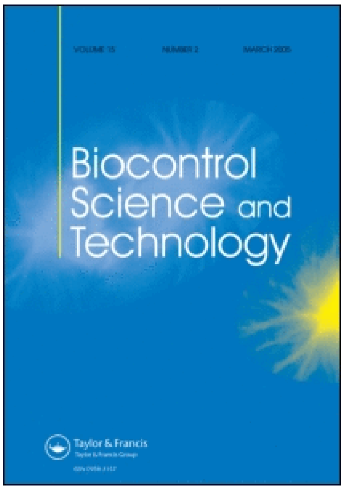

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REVIEW

Assessing potential biological control of the invasive plant, tree-of-heaven, *Ailanthus altissima*

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Abstract
Tree-of-heaven, *Ailanthus altissima,* is a deciduous tree indigenous to China and introduced into North America and Europe. It is a serious threat to ecosystems in introduced areas, as the plant is very competitive, and also contains allelopathic chemicals that may inhibit growth of surrounding native plants. In addition, the plant contains secondary chemicals that make it unpalatable to some insects. In this paper we assess potential biological control of this plant by reviewing literature associated with natural enemies of the plant from both its native and introduced regions in the world. Our literature surveys revealed that 46 phytophagous arthropods, 16 fungi, and one potyvirus were reported attacking tree-of-heaven, some apparently causing significant damage in China. Two weevils, *Eucryptorrhynchus brandti* and *E. chinensis*, are major pests of the plant in China and are reportedly restricted to tree-of-heaven, showing promise as potential biological control agents. Nymphs and adults of a homopteran insect, *Lycorma delicatula* and larvae of two lepidopteran species, *Samia cynthia* and *Eligma narcissus*, may also cause severe damage, but they are not host specific. Two rust fungi, *Aecidium ailanthi* J. Y. Zhuan sp. nov. and *Coleosporium* sp. have been reported on tree-of-heaven in China and are also promising potential candidates for biological control of the plant. Nine insect herbivores and 68 fungi are associated with tree-of-heaven in its introduced range in North America, Europe, and Asia. An oligophagous insect native to North America, the ailanthus webworm, *Atteva punctella*, may be a potential biocontrol agent for the plant. Among the fungal species, *Fusarium osysporum* f. sp. *perniciosum*, caused wilt of tree-of-heaven in North America and may have the potential to control the plant, but its non-target effect should be carefully evaluated. Our review indicates that there is potential for using insects or pathogens to control tree-of-heaven.

Keywords: *Biological control of weeds,* Ailanthus altissima*, invasive plant,* Eucryptorrhynchus brandti*,* Eucryptorrhynchus chinensis*,* Atteva punctella

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Introduction

Ailanthus altissima (Mill.) Swingle (Simaroubaceae), commonly known as tree-of-heaven but also called Chinese sumac, paradise-tree, or copal-tree, is a small to medium-sized deciduous tree native to China (Hu 1979). The species was introduced from China into Europe in 1751 and then introduced via Europe to North America in 1784 (Swingle 1916). It was also introduced directly from China to the west coast of the United States by Chinese gold miners in 1859 (Hu 1979). Tree-of-heaven is now widely distributed across the United States. The USDA Plants Database (http://plants.usda.gov/) records the plant in 42 states. Tree-of-heaven is widely naturalized in Europe, and has been introduced in South America, and Africa (Cozzo 1972; Kowarik 1983; Landolt 1993; Boukroute 1999). Tree-of-heaven forms dense, clonal thickets that displace native species (Cozzo 1972; Hu 1979). This tree has become a pest not only by outcompeting native vegetation, but also causes damage to roadways, sidewalks, sewer structures, and orchards with its extensive root system (Hu 1979). In addition to its prolific vegetative reproduction and extensive root system, tree-of-heaven has alleopathic effects on other tree species in invaded areas (Mergen 1959).

To date, there have been only limited efforts in developing biological control programs against tree-of-heaven (but see a short natural enemy list in Zheng et al. (2004)). Classical biological control is often regarded as a promising approach for suppression of exotic perennial weeds via screening, introduction and release of host-specific natural enemies from the pest's native range. Since no congeneric plant species of tree-of-heaven occur in North America, the risk to closely related non-target American native plants due to introduction of biological control agents could be minor, if the agents are host-specific to tree-of-heaven (Pemberton 2002). The purposes of this paper are to: (1) provide a brief review of the biology of tree-of-heaven and its impacts on invaded ecosystems; (2) summarize the literature documenting natural enemies of tree-of-heaven in China and its introduced range; and (3) assess potential biological control of tree-of-heaven using insects or pathogens.

Biology and ecology of tree-of-heaven

Tree-of-heaven is a deciduous species that bears yellowish-green male and female flowers on different trees (Hu 1979). Flowers appear from April to June in the Northern Hemisphere (Miller 2003). Pollination occurs in the spring. Fruits appear from August to October and seeds ripen from September to October. An individual tree can produce as many as 325,000 seeds per year and these seeds are easily dispersed by wind (Bory & Clair 1980). Seeds may have dormant embryos and need cold stratification before germination (Grime 1965; Goor & Barney 1968), but Graves (1990) reported that stratification was not necessary. Tree-of-heaven also reproduces asexually by sprouting from stumps or roots (Hu 1979) and it may produce root suckers as long as 27 m (Kiermeier 1983). As a result, it forms dense thickets in disturbed habitats. Sucker production is highest in trees that are 30–40 cm diameter and does not occur in trees that are >60 cm diameter (Lalhal et al. 1992).

Tree-of-heaven usually grows in disturbed areas (e.g., fallow agricultural lands, recently-harvested forest stands, road cuts, etc.). It prefers rich, moist soils but tolerates poor and dry soils. Since tree-of-heaven tolerates air pollution and may be able to sequester pollutants, it has been widely planted in urban areas worldwide to reduce environmental pollution (Kozyukina 1976; Marshall & Furnier 1981; Porter 1986).

Tree-of-heaven is widely used as an ornamental plant both in its native areas and where it has been introduced. In China, three cultivars of tree-of-heaven have been widely planted for reforestation by the timber industry (Li and Tao 1980). The leaves serve as forage for the cynthia moth, *Samia cynthia*, in sericulture, and the bark and fruit have been used in Chinese medicines. Tree-of-heaven is considered a favorable tree species in shelterbelts in western China due to its resistance to some insects, such as *Anoplophora nobilis* and *A. glabripennis,* as biologically active substances extracted from the bark and leaves of the plant including α-pinene, β-pinene and α-terpinene showed a strong toxic effect on these insects (Cao et al. 1997, 2004; Shao et al. 1998).

Tree-of-heaven is considered an invasive plant that is a threat to native ecosystems in North America and elsewhere in its introduced range. Its allelopathic properties negatively impact the growth of over 35 species of hardwood and 34 species of coniferous trees (Mergen 1959). In forest succession, tree-of-heaven may have a strong competitive advantage over desirable species like slash pine (*Pinus elliottii* Engelmann) and Monterey pines (*P. radiata* D. Don), since its toxins inhibit growth and germination of these plants (Voigt & Mergen 1962). However, the quassinoid ailanthone, a phytotoxic compound isolated from the plant, might have the potential of being developed into a broad spectrum herbicide, as it was reported to inhibit the growth of many weeds, such as garden cress (*Lepidium sativum* L.), pigweed (*Amaranthus retroflexus* L.) and barnyard grass (*Echinochloa crus-galli* L.) (Heisey 1990, 1996, 1997; Moradshahi et al. 2002). Disturbances may enhance the invasiveness of tree-of-heaven and its impacts on the native plant community (Call & Nilsen 2003). Tree-of-heaven may also cause economic losses and human health problems. The strong and aggressive root system of this plant is reported to cause damage to sewers and foundations (Hu 1979). The pollen of tree-of-heaven is recorded as a possible allergen (Ballero et al. 2003). Sap from tree-of-heaven may also induce a reaction when in contact with human skin (Derrick & Darley 1994).

Several conventional approaches have been employed to control tree-of-heaven. Manual removal and cutting should be effective for young seedlings in small infestations but it may be impossible to eliminate the entire root system. However, manual cutting may also stimulate resprouting and increased overall stand density (Burch & Zedaker 2003). In addition, these efforts are labor-intensive and do not work well for larger trees. Mechanical control may be prohibitive when the plant grows on steep slopes. Chemical herbicides can be applied as foliar, basal bark, cut stump, or hack and squirt treatments (Pritchard 1981). Glyphosate-based herbicides (e.g., Roundup, Rodeo, Accord) and the selective herbicide, triclopyr (e.g., Garlon 4), may injure or kill the plant (Burch & Zedaker 2003). About 80–100% defoliation of tree-of-heaven was achieved after spraying 2-chloroethylphosphonic acid (Sterrett et al. 1971). The combination of Garlon 4 and Tordon K herbicides was more efficacious when applied together than applied alone (Burch & Zedaker 2003). However, large-scale and long-term herbicide application may raise environmental concerns as well as being expensive and time-consuming.

Records of tree-of-heaven natural enemies

Natural enemies of tree-of-heaven in its introduced range

Our literature search revealed 9 herbivorous insects and 68 fungi associated with tree-of-heaven in its introduced range in North America, Europe, and Asia (Table I). There are two moths, ailanthus webworm, *Atteva punctella* (Cramer) (Lepidoptera: Yponomeutidae), and cynthia moth, *Samia cynthia* (Drurvy) (Lepidoptera: Saturniidae), recorded on tree-of-heaven in North America. A beetle, *Maladera castanea* (Arrow) (Coleoptera: Scarabaeidae) was reported to feed on several tree species including tree-of-heaven in North America (Miller 2004). Citrus whitefly, *Dialeurodes citri* (Ashmead) (Homoptera: Aleyrodidae), which is an important citrus pest, also feeds on tree-of-heaven and many other plants (Pirone 1978). A termite, *Heterotermes indicola* (Wasmann) (Isoptera: Rhinotermitidae), was reported to feed on tree-of-heaven in Pakistan (Shakoor et al. 1991); however, it also attacks plum trees (*Prunus* sp.) in Pakistan (Salihah et al. 1992), and chili (*Capsicum annum* L.) in India (Basalingappa et al. 1982).

Many fungi are reported in the literature to be associated with tree-of-heaven in North America, Europe, and Japan (Table I), but little detailed information is available on their host specificity and impact on the tree.

Natural enemies of tree-of-heaven in China, its country of origin

More insect herbivores have been recorded in China compared to the small number of insects associated with tree-of-heaven in its introduced range. Our literature search revealed 46 phytophagous arthropod species in 22 families from five orders and 16 fungi associated with tree-of-heaven (Table II). The arthropod component of the fauna included: 18 Lepidoptera, 16 Coleoptera, seven Homoptera, two Hemiptera, and three Acari. Most were defoliators, but some attacked the bark or tunneled in stems, branches, or trunks. Two weevils, *Eucryptorrhynchus brandti* (Harold) and *E. chinensis* (Olivier) (Coleoptera: Curculionidae), are major pests of tree-of-heaven and apparently found only on this tree (Ge 2000). Larvae of several lepidopteran species (e.g., silk moth, *Samia cynthia* and *Eligma narcissus* (Cramer) (Lepidoptera: Noctuidae)) together with a planthopper, *Lycorma delicatula* (White) (Homoptera: Fulgoridae), were also recorded as important pests on tree-of-heaven, but they are not host specific (Li & Tao 1980; Yao & Liu 1993). There is little information on the host ranges of two bark beetles, *Xyleborus discolor* Blandford and *X. lewisi* Blandford (Coleoptera: Scolytidae), which need further study. A new mite species, *Aculops ailanthi* sp. nov. (Acari: Eriophyoidea), was recently collected from tree-of-heaven but no information is available on its host range (Lin et al. 1997). Among the fungi associated with tree of heaven, there are three rust fungi, three Ascomycetes, one Oomycetes and eight imperfect fungal species (Table II).

Important insect natural enemies of tree-of-heaven

Eucryptorrhynchus brandti *and* E. chinensis *(Coleoptera: Curculionidae)*

Both species occur widely in China, but mainly in northern, central, and southeastern areas (Xiao 1992). They share the same feeding niche and have very similar life histories. Both weevils are univoltine in north and central China. Larvae overwinter under the bark and adults overwinter in the soil near host trees (Ge 2000). Both of the

Table I. Phytophagous arthropods and pathogens associated with *Ailanthus altissima* in its introduced range.

Scientific names	Part(s) of tree attacked[a]	Distribution	Relative host specificity[b]	References
Lepidoptera				
Yponomeutidae				
Atteva punctella (Cramer)	Leaves	USA	O	Baker (1972) Pirone (1978)
Arctiidae				
Hyphantria cunea Drury	Leaves	USA	P	Pirone (1978)
Halisidota tessellaris (Smith & Abbot)		USA	P	Pirone (1978)
Lymantriidae				
Hemerocampa leucostigma (J. E. Smith)	Leaves	USA	P	Pirone (1978)
Saturniidae				
Samia cynthia (Drurvy)	Leaves	USA (introduced) Austria Italy	P	Baker (1972) Pruscha (1981) Arzone (1971)
Homoptera:				
Aleyrodidae				
Dialeurodes citri (Ashmead)	Leaves	USA	P	Pirone (1978)
Diaspididae				
Lepidosaphes spp.	Leaves	USA	P	Pirone (1978)
Coleoptera				
Scarabaeidae				
Maladera castanea (Arrow)	U	USA	P	Baker (1972)
Isoptera				
Rhinotermitidae				
Heterotermes indicola (Wasmann)	Branches	Pakistan	P	Shakoor (1991)
Fungi				
Aplosporella ailanthi	Dry twigs	USA	U	Farr et al. (1989)
Armillaria mellea Vahl ex Fr.	Root	USA	P	USDA-ARS-CRD* (1960) Pirone (1978) Farr et al. (1989)
Artrodia malocola		USA		Farr et al. (1989)
Botryodiplodia ailanthi (Cke.) Sacc.	Twigs	USA	U	USDA-ARS-CRD (1960) Farr et al. (1989)
Botryosphaeria ribis	Twigs	USA	U	Farr et al. (1989)
Botryosphaeria dothidea (Moug.:Fr.) Ces. & De Not.		USA	P	Pirone (1978) Farr et al. (1989) Sanchez et al. (2003)
Botryosphaeria obtuse (Schwein.) Shoemaker	Limb & twigs	USA		Farr et al. (1989)
Camarosporium berkeleyanum (Lev.) Sacc.	Twigs	USA	U	USDA-ARS-CRD (1960) Farr et al. (1989)
Cercospora glandulosa Ell. & Kellerm.	Leaves	USA	M	USDA-ARS-CRD (1960) Pirone (1978) Farr et al. (1989)
Cerrena unicolor TJV	Butt rot	USA	P	Farr et al. (1989)

Table I (*Continued*)

Scientific names	Part(s) of tree attacked[a]	Distribution	Relative host specificity[b]	References
Colletotrichum dematium (Person:Fries) Grove (=*Colletotrichum ailanthi* Tognini)	U	Japan	U	Anonymous (2000)
Colletotrichum gloeosporioides	Leaf	USA	U	Farr et al. (1989)
Colletotrichum tertium Grove	Twigs	USA	U	USDA-ARS-CRD (1960)
Coniothyrium insitivum Sacc.	Twigs	USA	P	USDA-ARS-CRD (1960) Pirone (1978) Martirosyan (1974)
Cristulariella moricola	Leaf spot	USA	P	Farr et al. (1989)
Cytoplea insitiva	Twigs	USA	U	Farr et al. (1989)
Cytospora ailanthi Berk. & Curt.	Twigs	USA	U	USDA-ARS-CRD (1960) Pirone (1978)
Cytospora sacculus (Schwein.) Gvritischvili	Twigs	USA	P	Farr et al. (1989)
Daldinia concentrica TJV	Trunks	USA	P	Farr et al. (1989)
Daedalea unicolor Fr.	Twigs	USA	U	USDA-ARS-CRD (1960)
Diaporthe medusaea Nits.	Twigs	USA	P	USDA-ARS-CRD (1960) Timmer (1974)
Diaporthe rudis (Fr.) Nitschke	Twigs	USA	P	Farr et al. (1989)
Dimerosporium robiniae Gerard	Leaves	USA	U	USDA-ARS-CRD (1960)
Diplodia ailanthi Cke.	Twigs	USA	U	USDA-ARS-CRD (1960)
Diplodia natalensis P. Evans	Twigs	USA	U	USDA-ARS-CRD (1960)
Dothiorella glandulosa	Bark	USA	U	Farr et al. (1989)
Eutypella glandulosa (Cke.) Ell. & Ev.	Branches	USA	U	USDA-ARS-CRD (1960) Farr et al. (1989)
Eutypella leprosa (Pers.) Berl.	U	USA	P	Farr et al. (1989)
Eutypella microcarpa Ell. & Ev.	Twigs	USA	U	USDA-ARS-CRD (1960)
Eutypella scoparia (Pers.:Fr.) Berl.	Twigs	USA	P	Farr et al. (1989)
Fusarium lateritium Nees	Twigs	USA	P	USDA-ARS-CRD (1960) Pirone (1978) Farr et al. (1989) Szabo (2000)
Fusarium oxysporum f.sp. *perniciosum*	Leaves	USA	U	Stipes and Ash (2001)
Glabrocyphella ailanthi	Bark	USA	U	Farr et al. (1989)
Gloeosporium ailanthi Dearn. & Barth	Leaves	USA	U	USDA-ARS-CRD (1960) Pirone (1978)
Guignardia ailanthi (Grove) Sacc.	Twigs	USA	U	USDA-ARS-CRD (1960) Farr et al. (1989)

Table I (*Continued*)

Scientific names	Part(s) of tree attacked[a]	Distribution	Relative host specificity[b]	References
Haplosporella ailanthi. Ell. & Ev.	Dry twigs	USA	U	USDA-ARS-CRD (1960)
Helicobasidium mompa Tanaka	Roots	Japan	U	Anonymous (2000)
Hypoxylon rubiginosum (Pers.) Fr.	Dead limbs	USA	P	Farr et al. (1989)
Lasiodiplodia theobromae (Pat.) Griffon & Maubl.	Twigs	USA	P	Farr et al. (1989)
Leptothyrium petiolorum (Cke. & Ell.) Sacc.	Petioles	USA	U	USDA-ARS-CRD (1960) Farr et al. (1989)
Mycosphaerella ailanthi Ell. & Barth.	Twigs	USA	U	USDA-ARS-CRD (1960) Farr et al. (1989)
Nectria cinnabarina Tode ex Fr.	Trunks	USA	P	USDA-ARS-CRD (1960) Farr et al. (1989)
Hutchison (1999)				
Nectria coccinea Pers. ex Fr.	Trunks	USA	P	USDA-ARS-CRD (1960) Pirone (1978) Farr et al. (1989) O'Brien et al. (2001)
Phoma ailanthi Sacc.	Stems	USA	U	USDA-ARS-CRD (1960)
Phoma glandulosum	Petioles	USA	U	Farr et al. (1989)
Phomopsis ailanthi	Stems	Japan		
USA	U	Farr et al. (1989)		
Phellinus punctatus (Fr.) Pilát		USA	P	Farr et al. (1989)
Phyllosticta ailanthi Sacc.	Leaves	USA	P	USDA-ARS-CRD (1960) Dai (1979) Farr et al. (1989)
Phymatotrichum omnivora (Shear) Dug.	Roots	USA	P	Wright and Wells (1948) USDA-ARS-CRD (1960) Farr et al. (1989) Cook et al. (1995)
Physalospora obtuse (Schw.) Cke.	Twigs and branches	USA	U	USDA-ARS-CRD (1960) Pirone (1978)
Physalospora rhodina Cooke	U	USA	P	Pirone (1978) Ware and Snow (1976)
Placosphaeria spp.	U	Italy		Magnani (1975)
Polyporus lacteus Fr.	U	USA	U	USDA-ARS-CRD (1960)
Polyporus versicolor L. ex Fr.	U	USA	P	USDA-ARS-CRD (1960) Bonilla et al. (1995)
Rhizoctonia solani Kühn	Stems, seedlings	Japan	P	Anonymous (2000)
Rosellinia necatrix Prillieux	Roots	Japan	U	Anonymous (2000)

Table I (*Continued*)

Scientific names	Part(s) of tree attacked[a]	Distribution	Relative host specificity[b]	References
Schizophyllum commune Fr.	Wound rot	USA	P	USDA-ARS-CRD (1960) Farr et al. (1989) Yang and Beauregard (2001)
Stereum ochraceo-flavum (Schweinitz) Ellis	Twigs	USA	P	Farr et al. (1989)
Thyridium vesnitum	U	USA	U	Farr et al. (1989)
Trametes hirsuta (Wulfen) Pilát	Trunks	USA	P	Farr et al. (1989)
Trametes versicolor (L. ex Fr.) Pil.	White rot	USA	P	Farr et al. (1989)
Tubercularia vulgaris Tode	Twigs	USA	P	Farr et al. (1989)
Tyromyces chioneus (Fr.) P. Karst.	White rot	USA	U	Farr et al. (1989)
Trametes malicola Berk. & Curt	U	USA	U	USDA-ARS-CRD (1960)
Verticillium albo-atrum	Wilting	USA	P	USDA-ARS-CRD (1960) Pirone (1978) Farr et al. (1989)

[a] U: unknown. [b] P: polyphagous - attacks species from other plant families; O: oligophagous – primarily attacks species in the genus Ailanthus; M: monophagous – appears to only utilize on tree-of-heaven; U: unknown. * USDA-ARS-Crops-Research Division.

weevils prefer medium- to large-sized trees, and adults usually feed on buds, young leaves, and petioles. Following this damage, buds wilt and young leaves fall off. Female beetles lay eggs under the bark. After hatching, larvae bore into the trunk and feed on the cambium and then xylem. Pupae occur in tunnels in xylem. Hence, mortality caused by larval feeding is more severe than that by adults. Since adults do not readily disperse long distances, many individuals may occur in or on a single tree and eventually cause the death of the entire tree. In Huaibei, Anhui province of central China, more than 80% of *A. altissima* medium- to large-sized trees were damaged by these weevils and 37% of them died in 1996 (Ge 2000). In Anyang, Henan province of central China, 100% of medium-large-sized trees were attacked by these weevils and 12% died in 1991–1993 (Qin 1996). These two weevils are regarded as major pests on tree-of-heaven and control treatments are applied annually in China. After 4 years of integrated management of the weevils, including the use of insecticides, mass capture, and destroying infested trees, the damage and mortality rates of the tree dropped from 38.2 and 2.5% in 1992 down to 9.2 and 0.2% in 1996 in Lanzhou, Gansu province of northwestern China (Zhang et al. 2001). These two weevils may be host specific, as they were only found on tree-of-heaven. Therefore, they are considered promising biocontrol agents.

*Ailanthus webworm (*Atteva punctella*) (Lepidoptera: Yponomeutidae)*

The colorful ailanthus webworm, *Atteva punctella* is considered native to southern Florida and Central America and is currently distributed in eastern, central and

Table II. Phytophagous arthropods and pathogens associated with *Ailanthus altissima* in China.

Species	Part(s) of tree attacked[a]	Distribution[b]	Relative host specificity[c]	References
Arthropods				
Acari				
Eriophyoidea				
Aculops ailanthi Lin, Jin et Kuang	U	HN	U	Lin et al. (1997)
Tetranychidae				
Tetranychus urticae (Koch)	Leaves	Throughout China	P	Lei & Zhou (1998), Wang (1981)
Tetranychus viennensis Zacher	Leaves	Throughout China	P	Lei & Zhou (1998), Wang (1981)
Coleoptera				
Cerambycidae				
Acalolepta degener (Bates)	U	FJ, GD, GZ, HB, HLJ, HN, JL, JX, SC, SD, TW, YN, ZJ	P	Lei & Zhou (1998), Pu (1980)
Anoplophora glabripennis (Motschulsky)	Leaves, barks, branches	AH, BJ, GX, HB, HeB, HLJ, JL, JS, LN, SC, ZJ	P	Chen et al. (1959), Tang (1999)
Mesosa longipennis Bates	Leaves, barks, branches	GS, JS, TW, ZJ	P	Chen et al. (1959)
Trirachys orientalis Hope	Leaves, barks, branches	AH, BJ, GD, GS, GZ, FJ, HB, HeB, HeN, HLJ, HN, JS, JX, LN, SC, SD, ShaX, ShX, SH, TJ, TW, YN, ZJ	P	Chen et al. (1959), Xiao (1992)
Chrysomelidae				
Gastrolina depressa Baly	Leaves	GS, FJ, GD, GX, HB, HeN, HN, JS, SC, ShaX, ZJ	P	Lei & Zhou (1998), Yu et al. (1996)
Curculionidae				
Alcidodes waltoni (Bohemen)	Fruits, buds, stems	FJ, GD, GX, SC, TW, YN, ZJ	P	Lei & Zhou (1998), Chao & Chen (1980)
Desmidophorus hebes Fabricius	U	GD, GX, HB, HN, JS, JX, SC, SH, YN	P	Lei & Zhou (1998), Chao & Chen (1980)
Eucryptorrhynchus brandti (Harold)	Barks, leaves	BJ, HeB, HLJ, JS, SC, SD, SH, ShaX, ShX	M	Chao & Chen (1980), Xiao (1992)
Eucryptorrhynchus chinensis (Olivier)	Barks, leaves	BJ, HB, SC, SD, SH, ShaX, ShX, TJ	M	Chao & Chen (1980), Dong et al. (1993), Xiao (1992)
Eumolpidae				
Basilepta ruficolle (Jacoby)	U	FJ, GD, GX, GZ, HB, YN, ZJ	P	Lei & Zhou (1998), Tang et al. (1980)
Scarabaeidae				
Anomala corpulenta Motschulsky	Leaves	AH, HB, HeN, HLJ, HN, JS, JX, LN, NM, NX, SC, SD, ShaX, ShX, ZJ	P	Li & Tao (1980), Xiao (1992)
Holotrichia diomphalia Bates	Leaves	Throughout China	P	Li & Tao (1980), Xiao (1992)
Maladera orientalis Motschulsky	Leaves	Throughout China	P	Li & Tao (1980), Xiao (1992)

Table II (*Continued*)

Species	Part(s) of tree attacked[a]	Distribution[b]	Relative host specificity[c]	References
Proagopertha lucidula Faldermann	Leaves	AH, HLJ, GZ, LN, HB, HeN, HN, JS, JX, NM, NX, SC, SD, ShaX, ShX, ZJ	P	Li & Tao (1980), Xiao (1992)
Scolytidae				
Xyleborus discolor Blandford	Bark, trunk	FJ, HaiN, SC, TW, YN	P	Yin et al. (1984)
Xyleborus lewisi Blandford	Bark, trunk	HaiN, SC, TB, YN	P	Yin et al. (1984)
Hemiptera				
Pentatomidae				
Erthesina fullo (Thunberg)	Fruits, younger leaves and stems	AH, FJ, GD, GX, GZ, HaiN, HB, HeB, HeN, HN, JX, JS, LN, NM, SC, ShaX, ShX, YN, ZJ	P	Lei & Zhou (1998), Zhang (1985)
Palomena angulosa Motschulsky	U	HLJ, JX, LJ, SC, ShaX, ZJ	P	Lei & Zhou (1998), Zhang (1985)
Homoptera				
Cicadellidae				
Cicadella viridis (Linnaeus) Syn: *Tettigoniella viridis* (Linnaeus)	Leaves, stems	FJ, HB, HeB, HeN, HN, HLJ, JL, JX, LN, NM, QH, SC, SD, ShaX, ShX, XJ, TW, ZJ	P	Ge (1966), Xiao (1992)
Cicadidae				
Huechys sanguinea De seer	U	AH, FJ, GD, GX, GZ, HaiN, HB, HeN, HN, JX, SC, SD, ShaX, TW, YN	P	Lei & Zhou (1998)
Coccidae				
Ceroplastes japonicus Green	Leaves	FJ, GD, GS, GX, GZ, HB, HeB, HeN, HN, JS, JX, SC, ShaX, ShX, YN, ZJ	P	Lei & Zhou (1998), Wang (2001)
Diaspididae				
Pinnaspis theae (Maskell)	Leaves	FJ, GZ, TW, YN	P	Lei & Zhou (1998)
Dictyopharidae				
Orthopagus lunulifer Uhler	U	HB	M	Lei & Zhou (1998)
Fulgoridae				
Lycorma delicatula (White)	Leaves, stems	AH, GD, HB, HeB, HeN, JS, SD, ShaX, ShX, YN, TW, ZJ	P	Zhou et al. (1985), Anonymous (1992 a), Xiao (1992)
Margarodidae				
Icerya seychellarum (Westwood)	Leaves	AH, FJ, GD, GS, GX, GZ, HaiN, HB, HeB, HeN, HN, JS, JX, SC, SD, ShaX, TB, TW, YN, ZJ	P	Lei & Zhou (1998), Zhang and Zhao (1996)

Table II (*Continued*)

Species	Part(s) of tree attacked[a]	Distribution[b]	Relative host specificity[c]	References
Lepidoptera				
Arctiidae				
Hyphantria cunea (Drury)	Leaves	LN, SD, ShaX	P	Fang (2000), Xiao (1992)
Spilarctia melli Daniel Syn: *Lemyra melli* (Daniel)	Leaves	GS, GX, HB, HeB, HLJ, HN, JX, SC, ShaX, ShX, XZ, YN, ZJ	P	Fang (2000), Xiao (1992)
Geometridae				
Culcula panterinaria (Bremer et Grey)	Leaves	HeB, HeN, NM, SC, SD, ShaX, TW	P	Lei & Zhou (1998), IOZ-AC* (1982)
Meichihuo cihuai Yang	Leaves	ShaX	P	Xiao (1992)
Percnia giraffata Guenée	Leaves	AH, HeB, HeN, SC, ShaX, TW	P	Huang (1993), IOZ-AC* (1982)
Hepialidae				
Phassus excrescens Butler	Barks, stems Branches	HB, HLJ, LN, JL	P	Lei & Zhou (1998), IOZ-AS (1981), Xiao (1992)
Phassus miniatus Chu et Wang	Barks, stems Branches	HB	P	Lei & Zhou (1998)
Phassus nodus Chu et Wang	Barks, stems Branches	AH, HeN, JX, ZJ	P	Xiao (1992)
Lymantridae				
Lymantria xylina Swinhoe	Young stems	FJ, GD, TW	P	Zhao (1978), Xiao (1992)
Noctuidae				
Eligma narcissus (Cramer)	Leaves	FJ, HB, HeB, HN, SC, ShaX, YN, ZJ	P	Lei & Zhou (1998), Huang (1993), Chen (1999), Xiao (1992)
Pieridae				
Eurema hecabe (Linnaeus)	Leaves	Throughout China	P	Lei & Zhou (1998), Zhou (1994)
Talbotia naganum (Moore)	Leaves	GD, FJ, HB, JX, TW, ZJ	P	Wu (1995), Zhou (1994)
Pyralidae				
Dichocrocis punctiferalis (Guenée)	U	FJ, GD, GX, HB, HeB, HeN, HN, JS, JX, LN, SC, SD, ShaX, ShX, TB, TW, YN, ZJ	P	Lei & Zhou (1998)
Omphisa plagialis Wileman	U	BJ, HB, HeB, HeN, JS, LN, SC, SD, ShaX, ZJ	P	Lei & Zhou (1998)
Saturniidae				
Actias selene ningpoana Felder	Leaves	FJ, GD, GX, HaiN, HB, HeB, HN, JL, JS, JX, LN, SC, YN, TW, XZ, ZJ	P	Anonymous (1992 b), Zhu & Wang (1996)
Dictyoploca japonica Moore	Leaves	GD, GX, GZ, HaiN, HB, HeB, HLJ, HN, JL, JS, LN, ShaX, SC, SD, TW	P	Zhu & Wang (1996), He et al. (1999)

Table II (*Continued*)

Species	Part(s) of tree attacked[a]	Distribution[b]	Relative host specificity[c]	References
Samia cynthia cynthia (Drurvy)	Leaves	AH, FJ, GD, GS, GX, GZ, HaiN, HB, HeB, HeN, HN, JL, JS, JX, LN, SC, SD, ShaX, ShX, TW, XZ, YN, ZJ	P	Zhu & Wang (1996)
Samia cynthia ricina (Donovan) Syn: *Philosamia cynthia ricina* Donovan	Leaves	Throughout China	P	Wu (1995), Zhu & Wang (1996), Xiao (1992)
Fungi				
Albugo sp.	Leaves	NX	U	Shi and Ma (1998)
Aecidium ailanthi J.Y. Zhuang	Leaves	ShaX	M	Zhuang (1990)
Alternaria ailanthi T.Y. Zhang & Y.L. Guo	Leaves	BJ, SD, ShaX	M	Zhang & Guo (1998)
Cercospora glandulosa Ellis & Kellerm.	Leaves	HeB, HeN, JS	M	Dai (1979)
Cercospora ailanthi Syd.	Leaves	U	U	Wei (1979)
Coleosporium sp.	U	HeN	M	Yu and Ren (1999)
Cytospora ailanthi Berk. & M.A. Curtis	Leaves	XJ	M	Yuan (1997)
Nyssopsora cedrelae (Hori) Tranzschel	U	AH, GD, GX, GZ, HB, JX, HN, SD, TW	P	Dai (1979)
Phyllactinia ailanthi (Golovin & Bunkina) Y.N. Yu & S.J. Han	Leaves	AH, BJ, FJ, GS, HB, HN, JS, JX, NX, SD, ShaX	M	Anonymous (1987)
Phyllactinia corylea (Pers.) P. Karst. Syn: *Phyllactinia ailanthi* (Golovin & Bunkina) Y.N. Yu & S.J. Han	Leaves	AH, FJ, GX, GZ, HeB, HeN, HN, LN, JS, JX, SC, SD, ShX, ZJ, TW, YN	P	Dai (1979)
Phyllosticta ailanthi Sacc.	Leaves	HeB	M	Dai (1979)
Pseudocercospora ailanthicola (Patw.) Deighton	Leaves	HN	M	Liu and Guo (1998)
Pseudocercospora qinlingensis Y.L. Guo	Leaves	ShaX	O	Liu and Guo (1998)
Rhizoctonia solani J.G. Kühn	Stems, seedlings	NH	P	Li & Tao (1980)
Schizophyllum multifidum (Batsch) Fr.	U	ShaX	O	Dai (1979)
Uncinula delavayi Pat.	Leaves	JS, SC, YN	P	Anonymous (1987), Dai (1979)
Uncinula picrasmae Homma	Leaves	HB	M	Anonymous (1987)
Virus				
Portvirus	Leaves	BJ	P	Yao et al. (1993)

[a] U, unknown. [b] Abbreviated names of Chinese provinces: AH, Anhui; BJ, Beijing; FJ, Fujian; GX, Guangxi; GZ, Guizhou; HaiN, Hainan; HB, Hubei; HeB, Hebei; HeN, Henan; HLJ, Heilongjiang; HN, Hunan; JL, Jilin; JS, Jiangsu; JX, Jiangxi; LN, Liaoning; NM, Inner Mongolia; NX, Ningxia; SC, Sichuan; SD, Shandong; SH, Shanghai; ShaX, Shanaaxi; ShX, Shanxi; TB, Tibet; TW, Taiwan; YN, Yunnan; ZJ, Zhejiang. [c] P, polyphagous – attacks species from other plant families; O, oligophagous – primarily attacks species in the genus Ailanthus; M, monophagous – appears to only utilize tree-of-heaven; U, unknown. All information based on literature records alone. ● IOZ-AS Institute of Zoology, Academia Sinica.

southern USA (Powell et al. 1973). Its original native host is the paradise tree, *Simarouba glauca* DC., which is also in the family, Simaroubaceae (Bawa & Opler 1978). *S. glauca* is a medium-sized tree found from Panama northward through Central America to southern Florida and in the West Indies (Bawa & Opler 1978). Besides tree-of-heaven and paradise tree, no other plants have been reported to be hosts of *A. punctella*. It is believed that the moth has expanded its US distribution due to the rapid spread of its novel host, tree-of-heaven, over the last 130 years (Powell et al. 1973). However, a recent collection in Ottawa, Canada suggests that it might have an alternative host as no tree-of-heaven grows in Ottawa, or it migrates to cold areas (http://www.heiconsulting.com/dls/02401.html).

A. punctella larvae feed on leaves and produce nests on the plant by pulling two to three leaflets around a network of loose webbing (Chatfield et al. 2001). Serious damage may be found on seedlings, suckers and saplings since late instar larvae also attack bark and twigs. Pupation occurs in the larval webs (Ilg 1911) and *A. punctella* adults may overwinter but no further information is available regarding how and where they overwinter, in particular in cold areas (Powell et al. 1973). Moths are present from April to October in Ohio (Rings & Metzler 1999).

Besides *A. punctella,* several other species in the genus *Atteva* also have limited host ranges associated with plant species in the family Simaroubaceae (Powell et al. 1973). Native to northern Mexico and the southwestern United States, *Atteva exquisita* Busck prefers species in the genus *Castela* in California, but many larvae could not successfully develop on tree-of-heaven in laboratory tests (Powell et al. 1973). In India, *Atteva fabriciella* Swed. is a major pest of *Ailanthus triphysa* (Dennst.) Alston, an important matchwood species grown on a plantation scale (Varma 1986). In addition to damage to tender leaves and terminal shoots, *A. fabriciella* larvae may cause considerable damage to the inflorescence and tender fruits, resulting in 60% of mature seeds damaged on 8-year-old trees (Varma 1992). *A. triphysa* is its major host in India, but it also feeds on *Boswellia serrata* Roxb. ex Colebr., *Santalum album* L. and *Quassia indica* (Gaertn.) Noot. (Mohanadas and Verma 1984). Currently whether *A. fabriciella* attacks tree-of-heaven in India remains unknown.

Eligma narcissus *(Lepidoptera ×Noctuidae)*

The noctuid *Eligma narcissus* is a serious pest of tree-of-heaven in China (Li & Tao 1980; Su 1995). Larvae feed on leaves of the tree and may defoliate entire seedlings. Late-stadium larvae may also attack bark. A variety of chemical insecticides are used to control this pest in China and also in India, where it damages *Ailanthus triphysa* (Varma 1986; Su 1995). *E. narcissus* has a broad host range and attacks many tree species in China (Xiao 1992); thus, it is not a potential biocontrol agent for tree-of-heaven.

Lycorma delicatula *(Homoptera: Fulgoridae)*

Lycorma delicatula is a univoltine homopteran pest on tree-of-heaven in China (Xiao 1992). Both nymphs and adults feed on leaves, young stems and branches. These insects often occur in high numbers on individual trees in the field (Jianqing Ding, unpublished data). After plant hopper frass covers twigs and leaves of seedlings or trees, mold begins to grow on the frass, which may eventually lead to the death of seedlings or reduced tree growth (Li & Tao 1980). *L. delicatula* is widely distributed in

China, but with a broad host range including fruit and other economically important trees (Xiao 1992), and should not be considered as a biological control agent.

*Ailanthus silkmoth (*Samia cynthia*) (Lepidoptera: Saturniidae)*

The genus *Samia* Hubner contains 19 species that occur worldwide, but most are found in Asia (Peigler & Naumann 2003). Known as the ailanthus silkmoth or cynthia moth, *Samia cynthia* is native to northeastern China, but was introduced to many countries around the world between 1858 and 1870 for sericulture (Peigler & Naumann 2003). It was first introduced into North America in Philadelphia in 1861 and rapidly spread throughout the eastern States (Peigler & Naumann 2003), but commercial utilization of the moth was a failure in the United States. Current distribution of the moth is sporadic, occurring in urban areas along the coast from Massachusetts to Georgia, and west to Indiana (Covell 1984). Silkmoth larvae feed on leaves of tree-of-heaven and the first instars always congregate in high densities (Xiao 1992). Besides its preferred host, tree-of-heaven, *S. cynthia* feeds on as many as 15 other plant species in China (Xiao 1992) and also has hosts in several families including Lauraceae, Magnoliaceae and Oleaceae in Europe and North America (Peigler & Naumann 2003). In the United States, natural enemies, including predators and parasitoids, are regarded the major reason why *S. cynthia* cannot maintain high populations under field conditions (Frank 1986).

Important pathogens of tree-of-heaven

Rusts: Aecidium ailanthi *J.Y. Zhuan sp. nov.,* Coleosporium *sp. and* Nyssopsora cedrelae

Aeciospores of *Aecidium ailanthi* J.Y. Zhuan sp. nov. were found on the leaves of a tree-of-heaven specimen in a herbarium in Shaanxi Province, China (Zhuang 1990). It remains unknown if teliospores of the rust also infect tree-of-heaven. If both aeciospores and teliospores infect the same host, the rust fungus should be highly host-specific and may be considered as a potential biocontrol agent. Further studies with this fungus are warranted.

Coleosporium sp., a heteroecious rust fungus, is found on tree-of-heaven leaves in Zhengzhou, Henan Province in central China (Yu & Ren 1999). Although its spermogonia (0) and aecial (I) states remained unknown (Yu & Ren 1999), the common alternate hosts of 0 and I states for *Coleosporium* spp. are pines and almost all pine needle rusts are caused by fungi in this genus (Hansen & Lewis 1997).

Nyssopsora cedrelae is also recorded on tree of heaven in China (Anonymous 1987). *N. cedrelae* was collected from *A. altissima* in Hubei Province. Other hosts include *Cedrela chinensis* Juss., *C. sinensis* Juss., and *Spondias axillaries* (Dai 1979; Wei 1979). Fungi in the genus *Nyssopsora* Arthur are autoecious rusts, and 0 and I states are unknown (Cummins & Hiratsuka 1983).

Other pathogenic fungi

In our literature review of pathogens in China, 12 other fungi were recorded only from tree-of-heaven or congeneric species (Table II). *Alternaria ailanthi* sp. nov. caused leaf spots on tree-of-heaven in Shaanxi Province (Dai 1979). *Cercospora glandulosa,* collected from tree-of-heaven in Hebei, Jiangsu, and Henan provinces in China (Yuan 1997), also occurs on the plant in central and southern United States and South America (Farr et al. 1989). *Cercospora ailanthi* is recorded in central and southern United States and South America (Farr et al. 1989) and may also occur in China (Wei 1979). *Cercospora* sp. caused leaf spots and shot holes on tree-of-heaven in Henan Province, and severe infestations induced defoliation of seedlings and young trees (Li & Tao 1980). Some species in *Cercospora* have been studied for biological weed control either as mycoherbicide or as classic biological control agent. For instance, *C. rodmanii* has been used to control water hyacinth in south-eastern US and was introduced to the Republic of South Africa for controlling the same aquatic plant (Julien & Griffiths 1998). Another *Cercospora* species, *C. echii,* has been evaluated for its potential to control *Echium plantagineum* L. in Australia (Julien & Griffiths 1998). The two *Cercospora* species infecting *Ailanthus* may have potential as biological control agents for *A. altissima*, and their host ranges need to be evaluated. Other fungi caused leaf spots, and include *Phyllosticta ailanthi* (Anonymous 1987), *Pseudocercospora ailanthicola*, and *P. qinlingensis* (Liu & Guo 1998). *Phyllactinia ailanthi* (=*P. corylea* (Pers.) Karst.), a fungus that causes powdery mildew, was recorded on tree-of-heaven in Beijing, Gansu, Shaanxi, Ningxia, Shandong, Jiansu, Anhui, Jianxi, Fujian, Hubei, Hunan, Liaoning, Henan, and Sichuan provinces (Dai 1979). This fungus also occurs on tree-of-heaven in Virginia (United States), Europe and Korea (Dai 1979). *Uncinula delavayi* and *U. picrasmae* are two additional fungi that cause powdery mildew on tree-of-heaven (Dai 1979; Anonymous 1987). *Cytospora ailanthi* causes cankers on branches in China (Yuan 1997) and also occurs in the United States (USDA-ARS Crops Research Division 1960; Pirone 1978). A white rust fungus, *Albugo* sp., reported from yellow leaves and brown leaves of tree-of-heaven in Ningxia, Northwest China (Shi & Ma 1998), needs to be identified first, and evaluated if it has biological control potential. *Albugo tragopogonis*, an accidentally introduced white fungus of Canadian origin, has caused heavy reduction in plant weight and seeds of annual ragweed (*Ambrocia artemisiifolia* L.) in former USSR (Julien & Griffiths 1998).

In the introduced regions of tree-of-heaven, *Fusarium osysporum* f. sp. *perniciosum* and *Verticillium albo-atrum* are two important pathogens attacking the plant. *F. osysporum* f. sp. *perniciosum,* was isolated from dying tree-of-heaven in the United States, but it also caused wilt of many other plants, such as mimosa (*Albizia julibrissin*), another invasive plant in North America (Stipes & Phipps 1975; Jenkins 2004). Species in *Fusarium*, such as *Fusarium oxysporum* var. *orthoceras* and *F. solani*, have been used to control the native weed, broomrape (*Orobanche* spp.) in several countries in Europe and China (Julien & Griffiths 1998). Wilting and mortality of tree-of-heaven infected by *V. albo-atrum* has also been reported in the United States and this fungus caused leaves to turn yellow and drop prematurely, followed by the death of branches or the entire tree (USDA-ARS Crops Research Division 1960; Pirone 1978), however, it also infected many other tree species, including maples, elms, black locust, ash, etc. (Farr et al. 1989; Stipes & Hansen 2000.). Using indigenous fungi with broad host range to develop mycoherbicides against invasive plants may be possible (De Jong et al. 1996; Becker et al. 1999; Green 2003); however, appropriate technology needs to be developed, for example, application of the agents directly to cut surfaces to avoid nontarget exposure (as some fungi require a wound through which to enter the host) and careful risk assessment should be done before any field application.

Other pathogens also infect tree-of-heaven. *Schizophyllum commune* (= *Schizophyllum multifidum* (Batsch) Fr.), saprophytic or sometimes parasitic on various plants, was collected on *Ailanthus* spp. in Shaanxi Province in China (Dai 1979), and it also occurs on tree-of-heaven and many other plants in the United States (Farr et al. 1989). A potyvirus was isolated and found to cause mosaic symptoms on tree-of-heaven in Beijing, China, but further host range testing found that the virus could infect 21 out of 23 plant species within six families, including Solanaceae, Leguminosae, Chenopodiaceae, Cucurbitaceae, Cruciferae, Amaranthaceae (Yao & Liu 1993). *Rhizoctonia solani* causing damping-off of tree-of heaven was found in Zhengzhou, Henan Province (Li and Tao 1980), and it was also found in Japan (Anonymous 2000) and the United States (Farr et al. 1989). But this fungus can attack many plants in many families (Farr et al. 1989). An unidentified root rot is also one of the major diseases of tree-of-heaven in China. It mainly infects 2–3-year-old seedlings. Infected roots turn yellowish brown or dark followed by wilting and death. A survey showed that 2.4–52.9% of the seedlings were damaged by root rot in Ningxia province of northwestern China in 1996 (Tian & Zhao 1997). None of these fungi appear to have any potential as biological control agents.

Biological control of tree-of-heaven: A prospect

Tree-of-heaven is threatening native ecosystems in its introduced range. The ineffectiveness of conventional weed control methods against this invasive tree may justify the development of a biological control program as a management alternative. Our literature search reveals 46 phytophagous arthropod species attacking the plant. Two weevils, *E. brandti* and *E. chinensis*, are regarded as promising biocontrol agents based on their damage and limited host ranges. Host ranges of both weevils are being studied in China and in the USA; preliminary results suggest that they only feed on tree-of-heaven (Jianqing Ding et al., unpublished data). In China, we have never seen these two weevils on any plants other than tree-of-heaven. A diverse complex of fungi, especially two rusts (*Aecidium ailanthi* sp. nov. and *Coleosporium* sp.), may also warrant study as potential biocontrol agents. Field surveys and laboratory tests are being conducted in China, under a cooperative agreement between the USDA Forest Service-Forest Health Technology Enterprise Team and the Institute of Biological Control, Chinese Academy of Agricultural Sciences, to evaluate potential natural enemies for biological control of tree-of-heaven in the United States.

Using North American indigenous natural enemies to control tree-of-heaven may also be possible. The native ailanthus webworm, *A. punctella,* occurs widely in North America and has a very narrow host range. The original native host of this moth is *S. glauca*, but it has expanded its host range to include the exotic tree-of-heaven. It has subsequently spread far beyond its native range in southern Florida, following the spread of this new host in the United States. In its new distribution in the north and central United States, it is not yet known whether the moth attacks other plant species besides tree-of-heaven, or whether *A. altissima* and *S. glauca* are equally-preferred hosts. If *A. punctella* only utilizes tree-of-heaven, augmentation and release of this native insect may be possible in those areas, since its native host (*Simarouba glauca*) only occurs in southern Florida. It will be worthwhile to investigate whether a new host race of the moth has formed on tree-of-heaven, which could provide a more host-specific agent. Recently, several new host races of phytophagous insects have reportedly formed after they colonized new exotic plants in North America (Carroll et al. 1998; Filchak et al. 2000; Sheldon & Jones 2001). In addition to the native ailanthus webworm, native pathogens in North America, such as *Fusarium oxysporum* f. sp. *perniciosum* may also be developed as mycoherbicides to control tree-of-heaven and currently study of this fungus is being conducted in the United States (Jenkins 2004).

Our literature review suggests that biological control is a potential promising alternative for managing tree-of-heaven. This technique needs to be evaluated and integrated into an invasive species management plan. Our review is based on a thorough literature search. We collected information from international databases, such as BIOSIS, CAB, and major Chinese databases (in Chinese), and Chinese books on forest and agricultural fauna, as well as internet information. We believe the natural enemies associated with tree-of-heaven in China have been well-documented, as this plant is very important in forestation and ornamental plantation in many provinces in China. There may be other insects/fungi that are not major pests of tree-of-heaven and have not been reported in the published literature/information. Extensive field surveys will be necessary to identify the complex of insects and pathogens, either in native or introduced ranges, associated with the plant. Study of the plant's life history, ecology, population biology, and genetics need to be undertaken in its native range in order to effectively manage this invasive plant and predict its future spread. Host-range tests and risk assessments with selected insects or fungi should be given high priority to avoid any potential post-release threats to non-target plants in introduced areas. In addition, long-term monitoring is necessary to evaluate the impacts of biological control agents on the target weed and its associated plant and animal communities.

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References

Anonymous. 1987. Flora Fungorum Sinicorum Erysiphales (in Chinese). Beijing: Science Press.

Anonymous. 2000. Common names of plant diseases in Japan. Tokyo: Japan Plant Protection Association.

Ballero M, Ariu A, Falagiani P. 2003. Allergy to *Ailanthus altissima* (tree of heaven) pollen. Allergy 58:532–533.

Basalingappa S, Holihosur SN, Kulkarni KA, Veeranna G. 1982. Infestation of the termite, *Heterotermes indicola* Wasmann on chilli (*Capsicum annum*) plants and its control (*Rhinothermitidae*: Isoptera). Indian Zoologist 6:55–59.

Bawa KS, Opler PA. 1978. Why are pistillate inflorescences of *Simarouba glauca* eaten less than staminate inflorescences. Evolution 32:673–676.

Becker EM, Ball LA, Hintz WE. 1999. PCR-based genetic markers for detection and Infection frequency analysis of the biocontrol fungus *Chondrostereum purpureum* on sitka Alder and trembling aspen. Biological Control 15:71–80.

Bory G, Clair MD. 1980. Morphology, ontogeny and cytology of trichomes of *Ailanthus altissima*. Phytomorphology 30:67–78.

Boukroute A. 1999. Present state of street trees in Oujda City (Eastern Morocco): special case of plane tree. In: Lemattre M, Lemattre P, Lemaire F, editors. Proceedings of the International Symposium on Urban Tree Health, Paris, France, 22–26 September 1997. Acta Horticulturae. pp 377–381.

Burch PL, Zedaker SM. 2003. Removing the invasive tree *Ailanthus altissima* and restoring natural cover. Journal of Arboriculture 29:18–24.

Call LJ, Nilsen ET. 2003. Analysis of spatial patterns and spatial association between the invasive tree-of-heaven (*Ailanthus altissima*) and the native black locust (*Robinia pseudoacacia*). American Midland Naturalist 150:1–14.

Cao B, Li Z, Ji X, Xu X. 2004. A study on scattering effects of the extracts from *Ailanthus altissima* on *Anoplophora glabripennis*. Journal of Nanjing Forestry University (Natural Sciences Edition) 28:47–49 (in Chinese).

Cao B, Xu Y, Lu W, Li S. 1997. Analysis of the chemical composition of several insect-resistant tree species and the mechanism(s) for their resistance. IV. The toxic effect of the chemical standard samples of several biologically active substances on longhorn beetle. Ningxia Journal of Agricultural and Forestry Science and Technology 6:1–3 (in Chinese).

Carroll SP, Klassen SP, Dingle H. 1998. Rapidly evolving adaptations to host ecology and nutrition in the soapberry bug. Evolutionary Ecology 12:955–968.

Chatfield JA, Boggs JF, Draper EA, Mathers H, Stone AK. 2001. Insect and Mite Activity Noted in Ohio Nurseries and Landscapes: 2001. Special Circular 186-02, The Ohio State University. Ohio Agricultural Research and Development Center.

Covell C. 1984. A field guide to the moths of eastern North America. Boston, MA: Houghton Mifflin Co.

Cozzo D. 1972. Initial behaviour of *Ailanthus altissima* in an experimental plantation. Revista Forestal Argentina 16:47–52 (in Spanish).

Cummins GB, Hiratsuka Y. 1983. Illustrated genera of rust fungi. Revised Edition. St. Paul, MN: American Phytopathological Society.

Dai F. 1979. Sylloge Fungorum Sinicorum (in Chinese). Beijing: Science Press.

De Jong MD, Sela E, Shamoun SF, Wall RE. 1996. Natural occurrence of *Chondrostereum purpureum* in relation to its use as a biological control agent in Canadian forests. Biological Control 6:347–352.

Derrick EK, Darley CR. 1994. Contact reaction to the tree of heaven. Contact Dermatitis 30:178.

Farr DF, Bills GF, Chamuris GP, Rossman AY. 1989. Fungi on plants and plant products in the United States. St. Paul, MN: The American Phytopathological Society Press.

Filchak KE, Roethele JB, Feder JL. 2000. Natural selection and sympatric divergence in the apple maggot *Rhagoletis pomonella*. Nature 407:739–742.

Frank KD. 1986. History of the ailanthus silk moth (Lepidoptera: Saturniidae) in Philadelphia: A case study in urban ecology. Entomological News 97:41–51.

Ge T. 2000. Preliminary study on the biology of *Eucryptorrhynchus brandti*. Newsletter of Forest Pests 2:17–18 (in Chinese).

Goor AY, Barney CW. 1968. Forest tree planting in arid zones. New York: Ronald Press.

Graves WR. 1990. Stratification not required for tree-of-heaven seed germination. Tree Planters' Notes 41:10–12.

Green S. 2003. A review of the potential for the use of bioherbicides to control forest weeds in the UK. Forestry 76:285–298.

Grime JP. 1965. Shade tolerance in flowering plants. Nature 208:161–163.

Hansen EM, Lewis KJ. 1997. Compendium of conifer diseases. St. Paul, MN: American Phytopathological Society Press.

Heisey RM. 1990. Evidence for allelopathy by tree-of-heaven (*Ailanthus altissima*). Journal of Chemical Ecology 16:2039–2055.

Heisey RM. 1996. Identification of an allelopathic compound from *Ailanthus altissima* (Simaroubaceae) and characterization of its herbicidal activity. American Journal of Botany 83:192–200.

Heisey RM. 1997. Allelopathy and the secret life of *Ailanthus altissima*. Arnoldia 57:28–36.

Hu S. 1979. Ailanthus. Arnoldia 39:29–50.

Ilg C. 1911. The life history of *Atteva aurea* Fitch. Entomological News 22:229.

Jenkins D. 2004. Virginia's big stink: Controlling Ailanthus. Available: http://www.cnr.vt.edu/forestupdate/Articles/bigstink.htm. Accessed 3 November 2004.

Julien MH, Griffiths MW. 1998. Biological control of weeds: a world catalogue of agents and their target weeds. 4th ed. Wallingford: CAB International.

Kiermeier P. 1983. Sucker formation in woody plants. Zeitschrift fur Vegetationstechnik im Landschafts und Sportstattenbau 6:60–64 (in German).

Kowarik I. 1983. Colonization by the tree of heaven (*Ailanthus altissima*) in the French mediterranean region (Bas-Languedoc), and its phytosociological characteristics. Phytocoenologia 11:389–405 (in Russian).

Kozyukina ZT. 1976. Some ecological and physiological indices of the gas resistance of woody plants. Biologicheskie-Nauki 7:103–107 (in Russian).

Lalhal JS, Ombir S, Singh O. 1992. Sucker development in *Ailanthus glandulosa* Desf. Van Vigyan 30:179–180.

Landolt E. 1993. Plant species which have expanded greatly in the city of Zurich in the last 150 years. Phytocoenologia 23:651–663 (in German).

Li RZ, Tao DW. 1980. Tree of Heaven (in Chinese). Henan, China: Henan People's Publishing House.

Lin FP, Jin CL, Kuang HY. 1997. A new genus and six new species of Eriophyidae from China (Acari: Eriophyoidea). Acta Entomologica Sinica 40:86–93 (in Chinese).

Liu X, Guo Y. 1998. Flora Fungorum Siniconrum. Beijing: Science Press.

Marshall PE, Furnier GR. 1981. Growth responses of *Ailanthus altissima* seedlings to SO_2. Environmental Pollution A 25:149–153.

Mergen F. 1959. A toxic principle in the leaves of Ailanthus. Botanical Gazette 121:32–36.

Miller J. 2003. Nonnative invasive plants of southern forests, a field guide for identification and control. Asheville, NC: USDA Forest Service Southern Research Station General Technical Report SRS–62.

Miller JH. 2004. *Ailanthus altissima* (Mill.) Swingle. Avaliable: http://www.na.fs.fed.us/spfo/pubs/silvics_manual/volume_2/ailanthus/altissima.htm. Accessed 5 November 2004.

Mohanadas K, Verma RV. 1984. A new host record for *Atteva fabriciella* (Lepidoptera: Yponomeutidae) a pest of Ailanthus. Journal of Tree Sciences 3:128.

Moradshahi A, Yaghmaee P, Ghadiri H. 2002. Allelopathic potential of tree of heaven (*Ailanthus altissima* Swingle). Iran Agricultural Research 21:27–38.

Peigler RS, Naumann S. 2003. A revision of the silkmoth genus Samia. San Antonio, TX: University of the Incarnate Word.

Pemberton RW. 2002. Future and appropriate targets for biological control of weeds in the eastern United States. In: van Driesche R, Blossey B, Hoddle M, Lyon S, Reardon R, editors. Biological control of invasive plants in the eastern United States. Morgantown, WV: USDA Forest Service Publication FHTET-2002-04. pp 375–386.

Pirone PP. 1978. Diseases and pests of ornamental plants. New York: John Wiley & Sons.

Porter JR. 1986. Evaluation of washing procedures for pollution analysis of *Ailanthus altissima* leaves. Environmental Pollution B Chemical and Physical 12:195–202.

Powell JA, Comestock JA, Harbison CF. 1973. Biology geographical distribution and status of *Atteva exquisita* (Lepidoptera: Yponomeutidae). Transactions of the San Diego Society of Natural History 17:175–186.

Pritchard GH. 1981. Spot-gun application of hexazinone for the control of tree of heaven. Proceedings of the Sixth Australian Weeds Conference, 1981. Vol. 1. Queensland Weed Society. pp 113–114.

Qin KX. 1996. Damage of *Eucryptorrhynchus brandti* to tree of heaven and its control. Entomological Knowledge 33:279 (in Chinese).

Rings RW, Metzler EH. 1999. The Lepidoptera of Portage County, Ohio. Research Bulletin 1195, Ohio State University Extension. Ohio Agricultural Research and Development Center, The Ohio State University.

Salihah Z, Sattar A, Khan AU, Khatoon R. 1992. Assessment of termite infestation to fruit trees in Peshawar area. Pakistan Journal of Zoology 24:169–170.

Shakoor A, Akhtar MS, Awan S. 1991. Feeding preferences of termites of Azad Kashmir. Pakistan Journal of Zoology 23:355–359.

Shao A, Wu Y, Liu W. 1998. An initial study of the comprehensive benefits of seven tree species disposition models in shelterbelts in the Ningxia plains. Journal of Beijing Forestry University 20:48–53 (in Chinese).

Sheldon SP, Jones KN. 2001. Restricted gene flow according to host plant in an herbivore feeding on native and exotic watermilfoils (Myriophyllum: Haloragaceae). International Journal of Plant Sciences 162:793–799.

Shi J, Ma Z. 1998. Ailanthus Albugo sp., a new desease found on wooden species. Plant Protection 24:52.

Sterrett JP, Baden JAI, Davis JT. 1971. Defoliation of oak, maple, and other woody plants with 2-chloroethylphosphonic acid [68-240] and potassium iodide [KI]. Proceedings of the Northeastern Weed Science Society, New York 25:376.

Stipes RJ, Hansen MA. 2000. Verticilium wilt of shade trees. Plant Disease Fact Sheets, Virginia Cooperative Extention. Virginia Polytechnic Institute and State University. p 2.

Stipes RJ, Phipps PM. 1975. *Fusarium oxysporum* f. sp. *perniciosum* on Fusarium-wilted mimosa trees. Phytopathology 65:188–90.

Su YY. 1995. Biology of *Eligma narcissu*. Forest Science and Technology Development 4:27–28 (in Chinese).

Swingle WT. 1916. The early European history and the botanical name of the tree-of-heaven, *Ailanthus altissima*. Journal of the Washington Academy of Sciences 6:409–498.

Tian GF, Zhao YH. 1997. Root rot of tree of heaven: Occurance and control strategy in Ningxia. Ningxia Journal of Agricultural and Forestry Science and Technology 1:30 (in Chinese).

USDA-ARS Crops Research Division. 1960. Agriculture Handbook 165. Index of plant diseases in the United States. Washington, DC: USGPO. p 531.

Varma RV. 1986. Ailanthus pests and their control. Evergreen 16:29.

Varma RV. 1992. Impact of *Atteva fabriciella* (Lepidoptera: Yponomeutidae) feeding on seed production in *Ailanthus triphysa*. Indian Journal of Forestry 15:326–328.

Voigt GW, Mergen F. 1962. Seasonal variation in toxicity of Ailanthus leaves on pine seedlings. Botanical Gazette 123:262–265.

Wei J-C. 1979. Fungal Identification Manual. Shanghai: Shanghai Science and Technological Press.

Xiao GR. 1992. Forest insects of China (in Chinese). Beijing: China Forestry Publishing House.

Yao J, Liu Y. 1993. Study on Ailanthus potyvirus. Forest Science 39:503–508 (in Chinese).

Yu Z, Ren G. 1999. New record of rust fungi in Henan Province (I). Acta Agriculturae Universitatis Henanensis 33:35–49 (in Chinese).

Yuan S. 1997. Diseases of trees and shrubs in China (in Chinese). Beijing: Science Press.

Zhang XF, Li T, Hu CL, Ma MS. 2001. Control of *Eucryptorrhynchus brandti*. Forest Pests In China Supplement:9–11 (in Chinese).

Zheng H, Wu Y, Ding J, Binion D, Fu W, Reardon R. 2004. Invasive plants of Asian origin established in the United States and their natural enemies Vol. 1. Morgantown, WV: USDA Forest Service FHTET 2004–05.

Zhuang J. 1990. Addition to Aecidium from China. Acta Mycologica Sinica 9:191–195 (in Chinese).